ELSEVIER

Powder Technology 124 (2002) 67–75

POWDER TECHNOLOGY

www.elsevier.com/locate/powtec

Acceleration of particle breakage rates in wet batch ball milling

C. Tangsathitkulchai*

School of Chemical Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand

Received 17 July 2001; received in revised form 1 October 2001; accepted 2 October 2001

Abstract

Batch wet grinding of 20 × 30 mesh quartz for slurry concentrations up to 56 vol.% solid showed an increase in the specific breakage rate of the top size feed as fines built up in the mill. The degree of this acceleration effect was represented by a parameter termed *the acceleration factor*, which depended both on the slurry concentration and the fineness of grinding. An empirical equation was developed to correlate the acceleration factor with slurry apparent viscosity, a characteristic size distribution and slurry concentration. The mechanism of rate acceleration was hypothesized to result from the ability of the top size particles to adhere on the grinding surfaces by means of liquid surface tension and pulp consistency and further influenced by the degree of flow turbulence prevailing in the charge. The overall effect gave rise to the classification of particles so that some remained in suspension and some resided on the grinding surfaces.

Keywords: Wet grinding; Ball mills; Slurry rheology; Breakage rate acceleration

1. Introduction

It is known that in a tumbling mill, a material can be ground faster in water than in air. The influence of liquid physical properties such as density, surface tension and viscosity on the rate of grinding has been the subject of numerous investigations [1–4]. In another approach, some investigators [5–7] chose to study the effect of bulk slurry rheology on the efficiency of grinding. In all cases, the purpose was to elucidate the role and effectiveness of liquid medium in wet grinding processes. Apart from the overall increase in grinding efficiency over the dry systems, another unique characteristic associated with wet grinding systems is the increase in the specific breakage rate of a mono-sized feed (S value of the well-known batch grinding kinetic equation) as fines accumulate during batch and continuous ball milling [8–14]. This type of grinding behavior was also noticeable even in a continuous industrial-scale ball mill, where size reduction and material transport through the mill occurred concurrently[15]. However, there has been no effort to study this inherent behavior of wet grinding in a more systematic manner. This paper presents further results on the quantitative analysis of acceleration of breakage rates observed in a batch ball milling system as well as the possible mechanisms involved.

2. Kinetics of batch grinding

The concept of treating batch grinding as a rate process in a manner similar to chemical reactor design has been well accepted in the analysis of various types of grinding mills and applied successfully in mill circuit design and simulation [16,17]. Due to its importance in the analysis of experimental data obtained in this work, a brief review of this kinetic approach is given first.

The range of particle sizes is divided into a number of finite, narrow sizes of the geometric sieve series ($\sqrt{2}$ or $\sqrt[4]{2}$) and the largest size labelled 1, the second 2 and so on, down to the final nth interval for materials smaller than some suitable size, usually a 400-mesh (38 μm) screen size. Consider a constant mass of solid charge being acted upon by grinding media. It is reasonable to assume that the disappearance rate of particles in a given size interval might be proportional to the amount of that size remaining. That is:

$$\mathrm{d}w_j(t)W/\mathrm{d}t = -S_j w_j(t)W, \tag{1}$$

* Tel.: +66-44-2244-90; fax: +66-44-2241-65.
E-mail address: chaiyot@ccs.sut.ac.th (C. Tangsathitkulchai).

0032-5910/02/$ - see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0032-5910(01)00477-6

where $w_j(t)$ is the mass fraction of size j particles in the total powder charge W at grinding time t and S_j is a constant called "the specific rate of breakage of size j". If S_j is constant during the course of grinding, the breakage is said to be "first order". Another important breakage parameter is known as "the primary breakage distribution", b_{ij}, which is the mean set of daughter fragments produced by primary fracture. It is defined as the weight fraction of broken products from size interval j, which appears in size range i on primary fracture, before rebreakage of these products. Thus,

$$\sum_{i=n}^{j+1} b_{ij} = 1, \quad i > j. \tag{2}$$

By performing a rate–mass balance on material in each size interval i present at time t in a mill,

$$\mathrm{d}w_i(t)W/\mathrm{d}t = -S_i w_i(t)W + \sum_{j=1}^{i-1} b_{ij}S_j w_j(t)W,$$

or

$$\mathrm{d}w_i(t)/\mathrm{d}t = -S_i w_i(t) + \sum_{j=1}^{i-1} b_{ij}S_j w_j(t), \quad n \geq i \geq j. \tag{3}$$

This equation is the basic size–mass balance for a first-order grinding system. Solution of this set of n differential equations gives prediction of the product size distribution at various grinding times, knowing the starting feed size $w_i(0)$, for given values of S_j an b_{ij}, which are determined experimentally. For breakage of the top size material (size 1), integration of the size–mass balance equation gives:

$$w_1(t) = w_1(0)\exp[-S_1 t],$$

or

$$\log w_1(t) = \log w_1(0) - S_1 t/2.303. \tag{4}$$

Therefore, a plot of log $w_1(t)$ versus t should give a straight line, if grinding proceeds in a first-order manner and the specific rate of breakage, S_1, determined from the slope of the plot.

3. Experimental

All grinding experiments were conducted in a steel laboratory cylindrical mill, fitted with six equally spaced semicircular lifters of 9.5 mm in radius and 25.4-mm-diameter chrome alloy steel balls were used as grinding media. Standard batch grinding tests were performed on a single size feed (20 × 30 mesh) of quartz in air and in water at various times and for various slurry concentrations, holding a fixed mass of solids in the mill. Size distributions of ground products were analyzed with a nest of $\sqrt{2}$ interval screens and a sieve shaker. Details of mill conditions are summarized in Table 1. Wet grinding tests were also performed under other conditions to elucidate the mechanism of observed acceleration in the specific rate of breakage.

Table 1
Mill and standard test conditions

Mill	
Diameter (m)	0.20
Length (m)	0.175
Speed (rpm)	76
Critical speed (rpm)	108
Fraction of critical speed (ϕ_C)	0.70
Grinding Media	
Diameter (m)	0.0254 (1 in.)
Density (kg m^{-3})	7800
Weight (kg)	7.34
Ball filling, fraction of mill volume (J)	0.30
Feed Solid	
Particle size	20 × 30 mesh (850 × 600 μm)
Powder filling, fraction of ball interstitial volume (U)	1.0
Solid density (kg m^{-3})	
quartz	2650
copper ore	2650
phosphate ore	3000

4. Results and discussion

4.1. Grinding results and acceleration factor

Fig. 1 shows the disappearance kinetics plots for dry grinding single size fractions of quartz and copper ore. It is clear that breakage of these materials follows the first-order law, that is, the accumulation of fines in the charge has no effect on the specific rate of breakage of the top size material (constant S value). Fig. 2 shows the corresponding first-order plots for wet grinding 20 × 30 mesh quartz over a range of slurry concentrations. It is noted that breakage of this top size fraction deviates from the normal first-order hypothesis previously observed with dry grinding, with acceleration in the specific breakage rate as the size environment becomes finer. With progressively higher solid concentrations the degree of rate acceleration tends to diminish, leading eventually to deceleration in the specific breakage rate at a very high slurry concentration.

As reported by Tangsathitkulchai and Austin [4], the acceleration in grinding rate as fines accumulating in the mill charge appeared to be the characteristic of the top size fraction. That is, the acceleration of the specific breakage rate also occurred even for smaller sizes providing the smaller sizes became the top sizes in the charge. This was

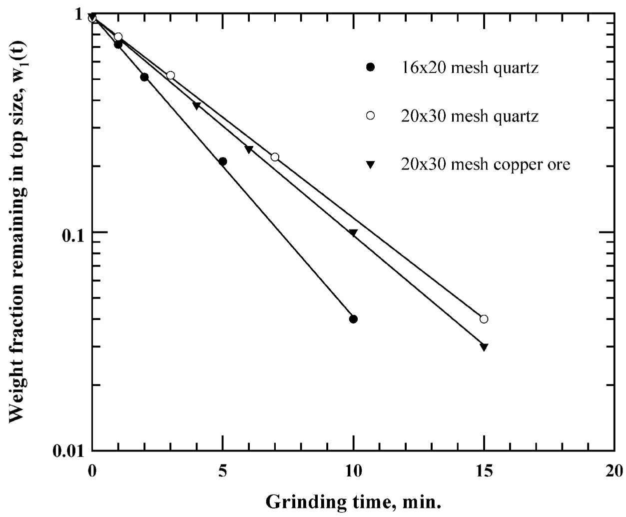


Fig. 1. First-order plots for batch dry grinding of single-size fractions of quartz and copper ore ($J = 0.3$; $U = 1.0$; 1-in. balls; $\phi_C = 0.70$).

confirmed by the simulated results on product size distributions, which showed that the breakage of particles smaller than the top size was approximately first-order. This phenomenon suggests that the effect is probably associated with a shielding mechanism, such that the top larger particles have better probability to be captured and get broken in the impact zones as compared to the smaller size particles. This classification of particles based on sizes is expected to be the result and role of slurry rheology and properties of the suspending liquid medium. It might be argued, however, that the increased specific breakage rate of the top size particles might be associated with the change in breakage mechanism or probably due to the top size fraction becoming weaker as grinding proceeds. However, the shape of product size distributions from wet grinding showed a normal constant slope of size distribution, typical of impact breakage with no indication of changes in breakage mechanisms. The weakening of particles during the course of batch grinding could be a material effect due to the presence of cracks and flaws within the particles or an environmental effect due to the influence of the surrounding liquid. However, since the starting feed fraction was preconditioned by short-time grinding to eliminate the abnormally weak particles and the dry grinding results did show a constant specific rate of breakage, the material effect cannot explain the rate acceleration occurring in wet grinding. In another aspect of particle weakening, the influence of water on the strength of quartz particles appears to be unlikely since the grinding time is rather short and quartz particles are usually inert in water.

The shape of the first-order plots, as shown in Fig. 2, suggests that the curves can be fitted by a second-order polynomial function of the form:

$$w_1(t) = w_1(0)\exp[-At - Bt^2], \tag{5}$$

where A and B are constants that depend on slurry concentration. To quantify the effect of breakage rate acceleration of top size particles, the acceleration factor, κ, is defined as:

$$\kappa = S_1(t)/S_1(0), \tag{6}$$

where $S_1(t)$ is the instantaneous specific rate of breakage at time t and is determined from the slope of the first-order plot, which from Eq. (5) gives,

$$S_1(t) = -\frac{\mathrm{d}}{\mathrm{d}t}\ln\left[w_1(t)/w_1(0)\right] = A + 2Bt, \tag{7}$$

and $S_1(0)$ is the initial breakage rate, determined from Eq. (7) at $t = 0$, i.e., $S_1(0) = A$. Therefore, from the definition of the acceleration factor: $\kappa = 1$ for normal first-order grinding; $\kappa > 1$ for grinding with acceleration effect; and $\kappa < 1$ for grinding with deceleration effect.

Fig. 3 gives the results of acceleration factor as a function of fineness of grinding expressed as percent of minus 200 mesh fines, for 20×30 mesh quartz feed. In general, the acceleration factor increases approximately linearly with the amount of fines produced and the degree of increase becomes less as the slurry concentration is increased. It can be estimated that the breakage of 20×30 mesh quartz fraction becomes practically first order, that is $\kappa = 1$, at the slurry concentration of about 58% solid by volume.

4.2. Correlations of the acceleration factor

It has been demonstrated that the acceleration of breakage rate of the top-size materials can be quantified in terms of the acceleration factor, κ, and that κ is a function of slurry concentration and fineness of grinding. Since slurry viscos-

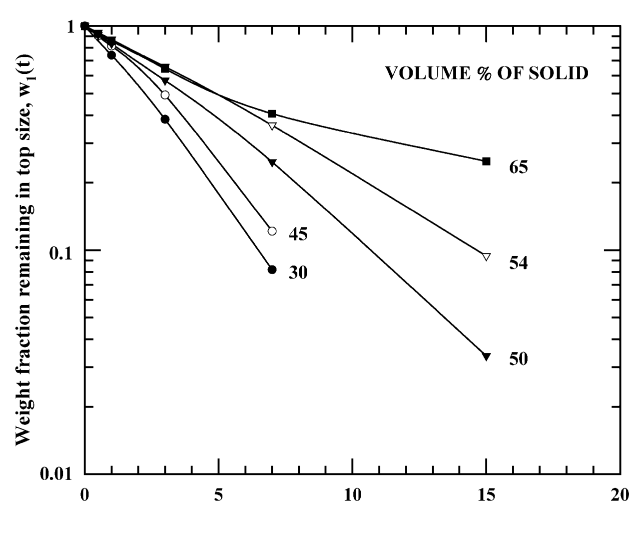


Fig. 2. First-order plots for batch grinding of 20×30 mesh quartz at various slurry concentrations ($J = 0.3$; $U = 1.0$; 1-in. balls; $\phi_C = 0.70$).

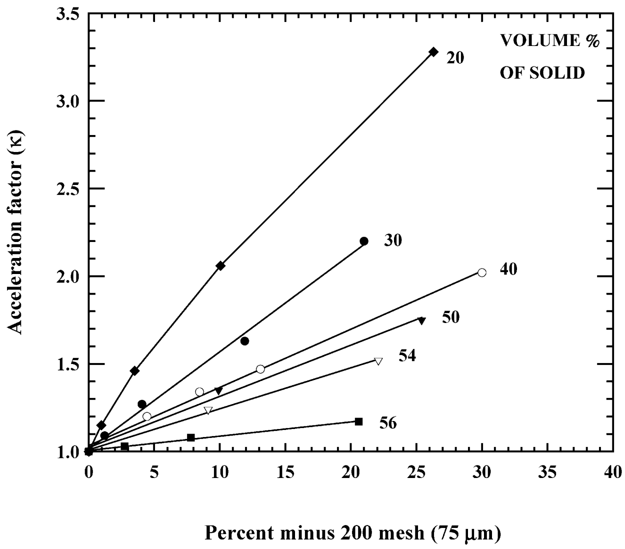


Fig. 3. Variation of acceleration factor with fineness of grinding for 20 × 30 mesh quartz batch ground in water at various slurry concentrations (J = 0.3; U = 1.0; 1-in. balls; ϕ_C = 0.70).

ity is dependent both on the slurry concentration and particle size distribution, it might be logical to correlate the acceleration factor with slurry viscosity, which in batch grinding increases with the grinding time.

Tangsathitkulchai and Austin [18] studied the rheology of concentrated slurries of particles produced by ball mill grinding. They found that the homogeneous particle suspensions showed a time-independent non-Newtonian character of ''pseudoplastic with yield stress followed by Bingham plastic behavior''. The basic equation used to describe the rheologic curve was given by:

$$\frac{\tau}{\mu_L} = \frac{\tau_Y}{\mu_L} + \left[\frac{\tau_{BY}}{\mu_L} + \frac{\mu_{PL}}{\mu_L}\frac{dv}{dy} - \frac{\tau_Y}{\mu_L}\right]Q, \tag{8}$$

where τ is the shear stress, dv/dy is the rate of shear, τ_y is the true yield stress, τ_{BY} is the Bingham yield stress, μ_{PL} is the Bingham plastic viscosity, μ_L is the viscosity of suspending liquid, and Q is a function that allows for pseudoplastic behavior at low shear rates. Eq. (8) can be expressed in terms of relative apparent viscosity, μ_a/μ_L, as:

$$\frac{\mu_a}{\mu_L} = \left[\frac{\tau_Y}{\mu_L} + \left(\frac{\tau_{BY}}{\mu_L} + \frac{\mu_{PL}}{\mu_L}\frac{dv}{dy} - \frac{\tau_Y}{\mu_L}\right)Q\right] \Big/ (dv/dy), \tag{9}$$

where μ_a is the apparent viscosity and equal to the ratio of shear stress and the rate of shear. The function Q was approximated with a single empirical function,

$$Q = 1 - \exp\left[-0.32\left(\frac{dv}{dy}\right)^{0.72}\right]. \tag{10}$$

The yield stresses and plastic viscosity were represented by the following correlations:

$$\frac{\tau_Y}{\mu_L} = (6500/k)^{4.48C^{1.35}}, \tag{11}$$

$$\frac{\tau_{BY}}{\mu_L} = 135(1000/k)^{6C^{2.1}}, \tag{12}$$

$$\log\left[\frac{\mu_{PL}}{\mu_L}\right] = \left[4.26 + \frac{1}{1 + \left[\frac{0.06}{(m-0.7)^2}\right]^{4.7}}\right] \times \left[\frac{C}{1-C}\right]^{1.1+\exp(-14.2m^{2.6})} [k]^{-0.21}, \tag{13}$$

where C is the solid volume fraction of the slurry, m and k are the distribution and size modulii of the fitted Rosin–Rammler particle size distribution, respectively. The range of application of the developed correlations covers m = 0.4–1.2, k = 10–200 μm, C = 0.20–0.60, and shear rate (dv/dy) = 0–200 s^{-1}.

Eqs. (9)–(13) were used to estimate the relative apparent viscosities of ground slurries for the breakage of 20 × 30 mesh quartz feed. In this work, it was assumed that these rheological correlations were applicable to the coarse grinding of the closely sized feed of quartz and since shearing history of slurry is complex and can be time- and position-dependent, the shear rate was assumed to be constant throughout the charge. An average shear rate of 100 s^{-1} was arbitrarily chosen to represent the average shear level of slurry over the course of batch grinding. For comparative purposes, any reasonable value of shear rate between 0 and 200 s^{-1} can be utilized. As a result of the complexity of the flow behavior of slurry in the mill, further work should be tried to estimate the average shear rate within the operating mill. One possible experimental arrangement is to measure the falling speed of a grinding ball through a uniform slurry suspension of known size distribution and concentration. The effective slurry viscosity can then be approximately estimated from appropriate empirical equations for settling velocities of large particles, and with the aid of Eqs. (9)–(13) the average shear rate can be computed.

Fig. 4 shows log–log plots of the acceleration factor as a function of relative apparent viscosity for quartz grinding at various slurry concentrations. It is seen that the acceleration factor depends not only on the viscosity but also on the slurry concentration. Therefore, viscosity alone cannot account for the phenomenon of breakage rate acceleration observed in wet ball milling. Visual observation of rotating mill charge through a clear plastic front cover revealed that slurry concentration affected the distribution of solid particles within the mill. Three slurry regimes were observed on increasing slurry concentration. They are: Regime I for a

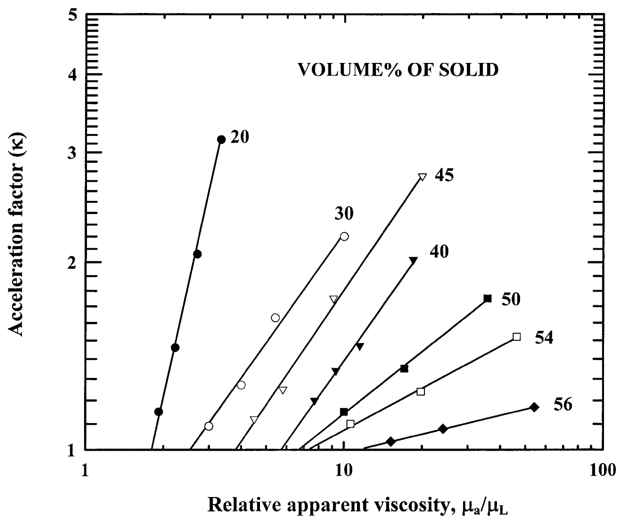


Fig. 4. Effect of slurry viscosity (at 100 s^{-1} shear rate) on the acceleration factor of quartz grinding (20 × 30 mesh feed; $J = 0.3$; $U = 1.0$; 1-in. balls; $\phi_C = 0.70$; $\mu_L = 0.001$ Pa s).

dilute slurry of 20 vol.% solid where a pool of slurry existed at the base of ball charge with characteristic of highly turbulent motion of slurry; Regime II for normal slurry concentrations of 30–45 vol.% solid, where the size of the pool appeared to gradually decrease causing the slurry to recede into the ball mass; and Regime III for dense slurry concentrations of greater than 50 vol.% solid, where a layer of particles started to deposit around the inner mill wall. In effect, the change in slurry viscosity through the variation in slurry concentration and fineness of grinding is to change the circulation path of the ball charge, as affected by the differences in particle deposition in the mill. In addition, the slurry nature of the charge will also affect the coating and wetting of the slurry on ball surfaces, giving rise to preferential grinding of adhered particles in the impact zones. The three slurry regimes previously mentioned appear to coincide with the results shown in Fig. 4. For the 20 vol.% solid slurry, the acceleration factor increases sharply with an increase in slurry viscosity, indicating that as size environment in the mill becomes finer the probability of particles being broken is increased, as compared to the usual first-order grinding. For slurries in the range 30–45 vol.% solid, the degree of increase in acceleration factor with viscosity becomes less and appears to be independent of concentration changes, indicating a similar ball–slurry interaction over this concentration range. For slurry concentrations in the range 50–56 vol.% solid, there is a progressive drop in the degree of acceleration, causing the breakage process approaching the first-order law ($\kappa \to 1$).

Fig. 5 shows the acceleration factor plot for grinding 20 × 30 mesh copper ore. The general effect of slurry concentration and viscosity on the acceleration factor is similar to the case of grinding quartz. The three slurry regimes, however, are not clearly distinguished but the degree of rate acceleration (slope of the plot) seems to decrease continuously with increased viscosity. The magnitude of the acceleration factor at the same viscosity and slurry concentration is lesser for the case of copper ore than that of quartz. It should be noted that Rosin–Rammler distribution modulus (m) of ground copper ore is 0.50 as compared to the value of 1.21 for quartz. The much flatter particle size distribution of copper ore, which indicates a more uniform distribution of particles in different size ranges, should in part explain the differences in the variation of acceleration factor with slurry viscosity for quartz and copper ore.

The acceleration factor curves shown in Figs. 4 and 5 can be fitted to the following power–law equation:

$$\kappa = \left(\frac{\mu_R}{\mu_R^*}\right)^{\alpha}, \tag{14}$$

where μ_R^* and α are constants of the equation. μ_R^* is the relative slurry viscosity that gives first-order grinding ($\kappa = 1$), while α is a measure of the degree of rate acceleration. Fig. 6 shows the effect of slurry concentration on α and μ_R^* when both parameters are normalized with the Rosin–Rammler distribution modulus (m), for quartz ($m = 1.21$), phosphate ore ($m = 0.90$) and copper ore ($m = 0.50$). It should be noted that the Rosin–Rammler size modulus (k) of the product size distribution decreases with the time of grinding, while the Rosin–Rammler distribution modulus (m) is relatively constant, being characteristic of a material and independent of the present milling period. The results in Fig. 6 show that the pattern for the drop of α/m with concentration can be divided into the three slurry regimes as discussed earlier, while μ_R^*/m increases exponentially with slurry concentration. As a result of this analysis, the acceleration factor for grinding 20 × 30 mesh

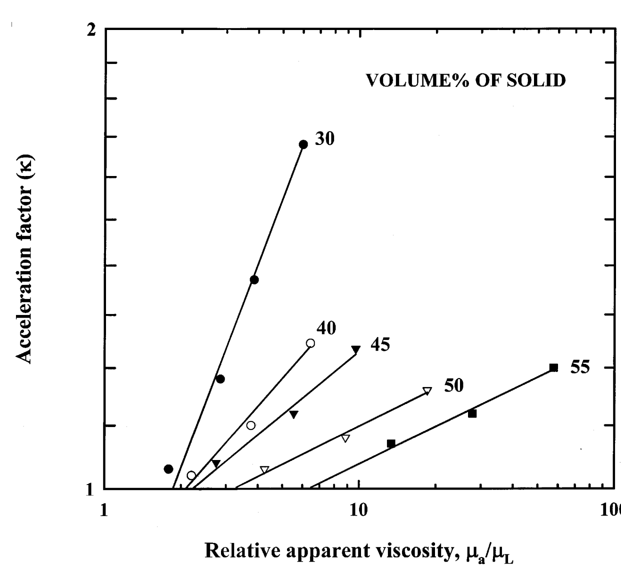


Fig. 5. Effect of slurry viscosity (at 100 s^{-1} shear rate) on the acceleration factor of copper ore grinding (20 × 30 mesh; $J = 0.3$; $U = 1.0$; 1-in. balls, $\phi_C = 0.70$; $\mu_L = 0.001$ Pa s).

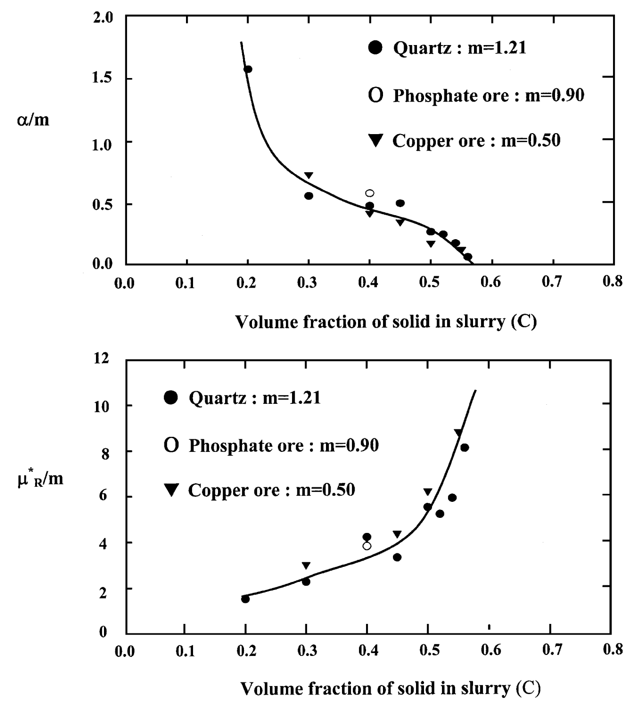
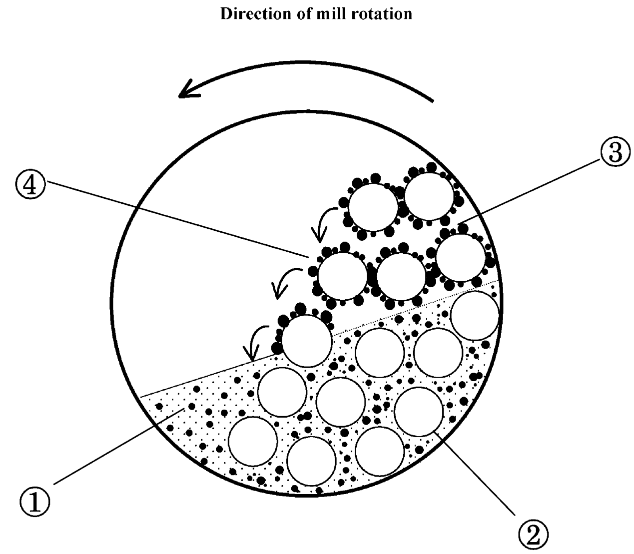


Fig. 6. Effect of slurry concentration on α and μ_R^* normalized with Rosin–Rammler distribution modulus (m).



① Pool of slurry existing at the base of ball charge
② Submerged ball mass ascending against stationary suspension of slurry, causing a liquid drag on the interstitial particles
③ Ball charge moving out from the slurry suspension with preferential adherence of larger particles on ball surfaces, caused by turbulence action of slurry flow
④ Preferential grinding of larger size particles in the cascading zones due to the blocking or shielding of large particles over smaller particles during ball-to-ball collision.

Fig. 7. Physical appearance of rotating mill charge, depicting various subprocesses contributing to the phenomenon of breakage rate acceleration of top-size particles.

feed material can be estimated from Eq. (14) and Fig. 6 as a function of slurry viscosity, knowing product size distribution (m and k) and slurry concentration.

4.3. Mechanisms of breakage rate acceleration

In addition to the quantification of acceleration in breakage rates of a single size feed material, various grinding tests were also performed to elucidate the underlying mechanisms of the rate acceleration. Previous grinding results and the observation of mill dynamics suggest that the increased breakage rates of the top-size material is primarily due to the acting of liquid surface tension and the stickiness of the slurry to hold particles on the ball surfaces. Once an adhered layer of particles is formed, larger particles are likely to receive more frequent impact during ball–ball collision due to their shielding action against the smaller size particles. This shielding effect is expected to be enhanced by the turbulence condition of slurry in the charge, thus causing the size classification of particles between ball surfaces and in the suspension. These hypotheses can be visualized from Fig. 7, which shows the configuration of rotating mill charge and the various subprocesses involved. Therefore, it would seem reasonable to propose that slurry coating on ball surfaces and the degree of flow turbulence are the prime mechanisms responsible for the acceleration of particle breakage rates in wet batch ball milling.

Some of the results in support of the above hypotheses are given as follows. Fig. 8 compares the first-order plots of 20 × 30 mesh quartz ground at 40 vol.% solid in liquids of different surface tensions, including n-hexane (1.84×10^{-2} N m^{-1}), methanol (2.45×10^{-2} N m^{-1}) and water (7.3×10^{-2} N m^{-1}). It is clear that as the liquid surface

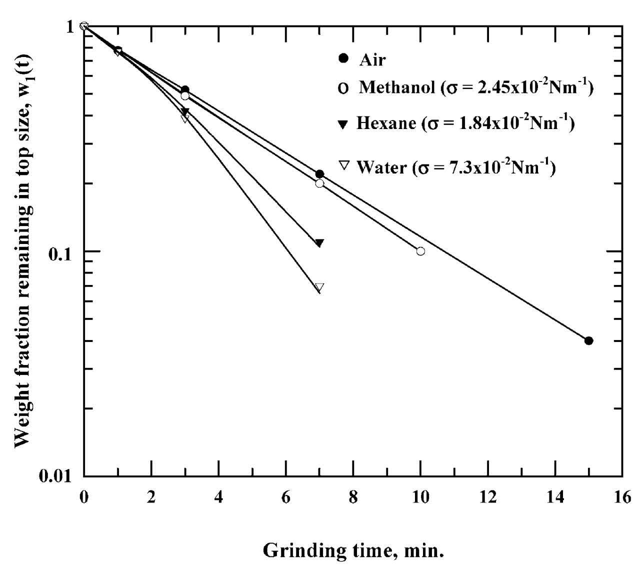


Fig. 8. Disappearance kinetics of 20 × 30 mesh quartz batch ground in fluids having different surface tensions ($J = 0.3$; $U = 1.0$; $\phi_C = 0.70$).

tension decreases, the breakage kinetic of wet grinding changes consistently towards that of the dry system. That is, the specific rate of breakage and the degree of rate acceleration tend to decrease with the lowering of liquid surface tension, thus giving a more uniform distribution of particles within the mill charge. Wet grinding of quartz was further conducted at 10 vol.% solid so that the whole ball mass was put under water, thus preventing the formation of adhered particle layer on ball surfaces. Fig. 9 shows the results. It appears that grinding in a submerged condition gives perfect first-order breakage, thus confirming the ball-coating hypothesis.

Another effect that is related to the role of slurry rheology on the rate acceleration is an increase in the acceleration factor with increased pulp viscosity during the course of batch grinding (see Figs. 3 and 4). It seems reasonable to suppose that some of the top larger particles can drain away from the cascading zone when the viscosity of the pulp is low, thus reducing the contact between particles and impacting balls. The presence of fine particles increases the consistency of the pulp and reduces this effect. To check this mechanism, batch grinding of 20 × 30 mesh quartz feed in various percentages of minus 400-mesh fines was performed. Results of the disappearance kinetics of breakage for grinding with fines addition at 40 vol.% solid are shown in Fig. 10. It is observed that the specific rate of breakage of the top size feed increases with increasing amount of suspended fine particles. The curves show almost straight lines because the added fines dominate over the production of extra fines in these short grinding times. Therefore, the increase in pulp viscosity as grinding proceeds should facilitate the adherence of large particles on the grinding media.

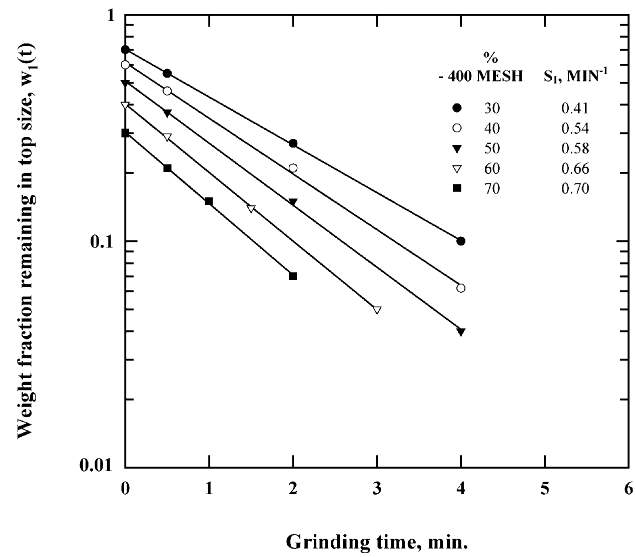


Fig. 10. Effect of added 400 mesh fines on the breakage rate of 20 × 30 mesh quartz (J = 0.3; U = 1.0; ϕ_C = 0.70; 40 vol.% solid).

The secondary effect of turbulence condition in the slurry charge was studied by running the mill at different rotational speeds. Fig. 11 shows that the degree of rate acceleration decreases progressively with the lowering of mill speed and hence the degree of slurry turbulence, giving first-order grinding for the speed less than 20 rpm. Another way of controlling the degree of turbulence is to change the viscosity of the liquid medium, using mixtures of glycerine and water of differing proportions. Fig. 12 shows that as the viscosity of the suspending medium increases, i.e., degree of

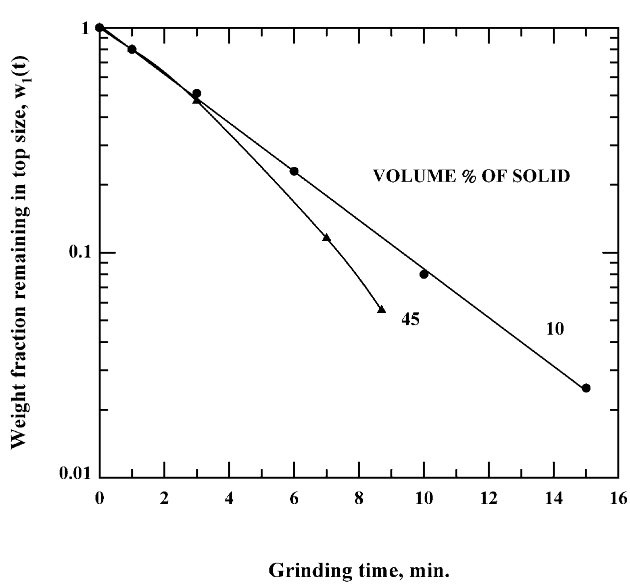


Fig. 9. First-order plots for batch wet grinding of 20 × 30 mesh quartz at normal and very dilute solid concentrations (J = 0.3; U = 1.0; ϕ_C = 0.70).

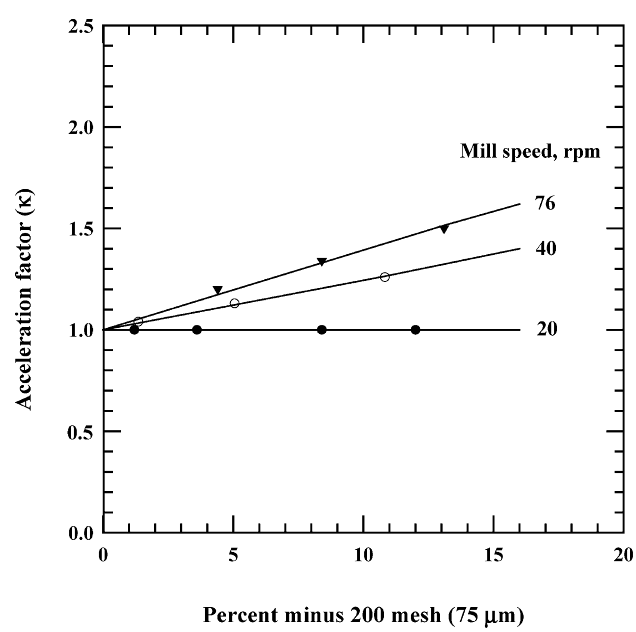


Fig. 11. Effect of mil rotational spped on the acceleration factor (20 × 30 mesh quartz; J = 0.3; U = 1.0; 40 vol.% solid).

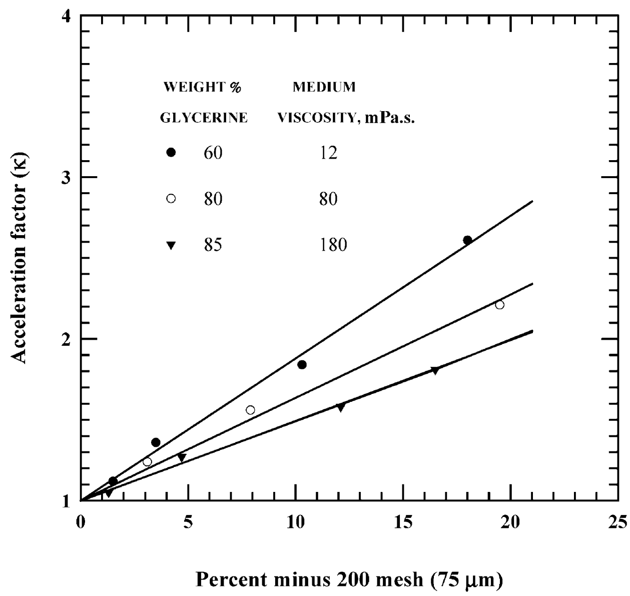


Fig. 12. Effect of liquid medium viscosity on the acceleration factor (20 × 30 mesh quartz; $J=0.3$; $U=1.0$; $\phi_C=0.70$; 40 vol.% solid).

turbulence decreases, the degree of breakage rate acceleration tends to decrease. However, the drop in the acceleration factor is not directly proportional to an increase in the viscosity of the liquid medium. Definitely, grinding in a too viscous medium can result in a slowing down of breakage rate of the top size material due to the thickening of coated particle layer on the grinding surfaces.

The turbulence condition of slurry in a mill can be further visualized by observing the movement of the ball charge. If the slurry is not too viscous, the rotation of the mill can create a strong turbulence in the slurry due to the movement of the ball mass up against the pool of slurry suspension (see Fig. 7). In addition, the rolling of cascading balls down into the suspension should also increase the degree of this turbulence action. As a result of the turbulence effect, it is likely that some particles that reside on the ball surfaces will experience a drag force being acted upon by the flow of the suspension. A simple force balance can be made on a single adhering sphere, based on the assumption that for the sphere to stay on the surface the combined surface tension force and the weight of particle must be greater than the drag force exerted by the fluid on the particle. Symbolically,

$$F_G + F_\sigma \geq F_D, \tag{15}$$

where, F_G is the force due to gravity, being equal to $\pi D_p^3 \rho_p g/6$; F_σ is the surface tension force, being equal to $\pi D_p \sigma$; F_D is the drag force, being equal to $C_D \rho_L u^2 A_P/2$; ρ_p is the particle density; ρ_L is the liquid density; σ is the liquid surface tension; A_P is the particle projected area, being equal to $\pi D_p^2/4$; D_P is the particle diameter; C_D is the drag coefficient, being a function of particle Reynolds number; u is the approach velocity of a fluid, taken as mill peripheral speed and g the acceleration due to gravity.

After substituting terms and rearrangement, one obtains:

$$D_p^2 - \left[\frac{3C_D\rho_L u^2}{4\rho_p g}\right] D_p + \frac{6\sigma}{\rho_p g} \geq 0.$$

Solving for D_p gives:

$$D_p \geq \left[\frac{3C_D\rho_L u^2}{8\rho_p g}\right] \pm \left[\left(\frac{3C_D\rho_L u^2}{8\rho_p g}\right)^2 - \left(\frac{6\sigma}{\rho_p g}\right)\right]^{1/2}. \tag{16}$$

As an example of calculation, the following numerical values are inserted into Eq. (16): $\rho_L = 10^3$ kg m^{-3} for water; $\rho_p = 2.65 \times 10^3$ kg m^{-3} for quartz particles; $C_D = 0.44$ for fully developed turbulent flow condition; $\sigma = 7.3 \times 10^{-2}$ N m^{-1} for water; $g = 9.8$ m s^{-2}; for mill speed of 76 rpm and mill diameter of 0.20 m, $u=(\pi)(76)(0.20)/(60) = 0.80$ m s^{-1}. This gives $D_p \geq 4.1 \times 10^{-3}$ m or 4.1 mm.

Therefore, under these normal wet grinding conditions, the minimum size for a given particle to stay on the grinding surface is about 4.1 mm or 5 mesh of screen size. However, in actuality, $D_{p,min}$ is expected to be less than this size since the presence of many particles can create an additional holding force due to friction between contacting particles. This simple calculation shows that in wet grinding the flow of slurry relative to the movement of ball charge can create a partition of particles based on sizes between the grinding media surfaces and in the suspension. This particle size classification is dependent on the mill conditions and process variables that affect the state of slurry flow.

5. Conclusions

Laboratory batch ball milling of 20 × 30 mesh quartz feed in water for a slurry concentration range of 20% to 56% solid by volume exhibited an acceleration of specific breakage rate of this size as fines accumulated in the mill. A quantitative measure of this acceleration effect was expressed in terms of the acceleration factor (κ), defined as the ratio of the instantaneous and initial specific breakage rates. For a given slurry concentration, the acceleration factor was found to increase with fineness of grinding but the degree of increase became less as the slurry concentration was progressively increased. In addition, the variation of κ with slurry concentration and viscosity followed a pattern that matched the various slurry flow regimes visually observed from the movement of mill charge. A general correlation was developed to enable the estimation of the acceleration factor from the product size distributions and slurry concentration. A qualitative model was proposed and experimental evidence given to support that the mechanism of acceleration in breakage rates of the top size materials involved the ability of larger particles to cling to the ball surfaces by virtue of liquid surface tension and consistency of the slurry pulp. The adherence of these larger particles can act to shield the smaller particles from receiving impact by the colliding balls. This shielding effect was further promoted by the degree of flow turbulence in the charge that caused some smaller size particles to be removed from the grinding zone.

Further experimental works should be extended to study the effect of other mill conditions on the acceleration factor such as mill size, ball size and density, ball and powder filling, and liquid and solid densities. These data should be of use in improving the simulation and design of large-scale wet grinding mills, since Austin and Tangsathitkulchai [15] reported that the simulation results for wet open-circuit grinding of a phosphate ore in a 3.35-m-diameter ball mill, scaled up from a laboratory mill assuming first-order breakage, gave a mismatch of the top size due to this acceleration effect.

References

[1] P.C. Kapur, A.L. Mular, D.W. Fuerstenau, Can. J. Chem. Eng. 43 (1965) 119.
[2] T.P. Meloy, D. Crabtree, in: H. Rumf, W. Pietsch (Eds.), Proc. 2nd European Symp. On Communution, vol. 57, Dechema Monographien, Amsterdam, 1967, p. 405.
[3] B. Clarke, J.A. Kitchener, Br. Chem. Eng. 13 (1968) 991.
[4] C. Tangsathitkulchai, L.G. Austin, Powder Technol. 59 (1989) 285.
[5] R.R. Klimpel, L.G. Austin, Powder Technol. 31 (1982) 239.
[6] R.R. Klimpel, Part. Sci. Technol. 38 (1984) 147.
[7] H. El-Shall, P. Somasundaran, Powder Technol. 38 (1984) 275.
[8] D.F. Kelsall, K.J. Reid, Inst. Min. Metall. 78 (1969) 198.
[9] J.A. Herbst, D.Eng Dissertation, Univ. California, Berkeley, California, 1971.
[10] J.H. Kim, PhD Thesis, Univ. of Utah, 1974.
[11] M.A. Berube, V. Berube, R. Le Houillier, Powder Technol. 23 (1979) 169.
[12] V.K. Gupta, D. Hodouin, Powder Technol. 32 (1982) 233.
[13] C. Tangsathitkulchai, L.G. Austin, Powder Technol. 42 (1985) 287.
[14] R.C. Klimpel, PhD Thesis, The Pennsylvania State University, 1988.
[15] L.G. Austin, C. Tangsathitkulchai, Ind. Eng. Chem. Res. 26 (1987) 997.
[16] L.G. Austin, K. Shoji, V. Bhatia, V. Jindal, K. Savage, R.R. Klimpel, Ind. Eng. Chem. Process Des. Dev. 15 (1976) 187.
[17] L.G. Austin, R.R. Klimpel, P.T. Luckie, The Process Engineering of Size Reduction: Ball Milling, SME-AIME, New York, 1984.
[18] C. Tangsathitkulchai, L.G. Austin, Powder Technol. 56 (1988) 293.